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The Archaean to Proterozoic igneous rocks of the Pilbara region, Western Australia –internationally significant geology of a globally unique potential geopark

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A B S T R A C T

The Pilbara region of Western Australia, covering some 500 km × 500 km, provides a diversity of Archaean to Proterozoic igneous rocks in a relatively compact area that records a younging southward crustal history of igneous activity, sedimentation, early life, tectonics, and metamorphism from the Archaean (3.6–2.7 Ga) to Proterozoic (2.5–1.8 Ga). The igneous rocks are variable in age, types of rocks, and mode of occurrence and, throughout the Precambrian, record varying igneous rock activity that appear related to several age-related geological settings: to north, the Archaean Pilbara Craton consists of a granitoid-and-greenstone complex; in the central region, there are Proterozoic sequences of volcanic rock, volcaniclastic rock, ironstone, chert, dolomite, shale, and intrusive dolerite sills and cross-cutting dolerite dykes; to the south, there are Proterozoic shale, dolomite, and chert with isolated granitic batholiths. Igneous activity begins in the Archaean with mafic and ultramafic volcanism alternating with sedimentation, and then granitoid cratonisation. This was followed by Proterozoic volcanic crustal accretion with mafic volcanic and volcaniclastic rocks, and by dolerite and gabbro sill and dyke intrusions, ending with isolated granite batholithic intrusions.

Igneous rocks in the Pilbara region are diverse: komatiite; mafic volcanic/volcaniclastic rocks; basalt; tuff/volcanic breccia/accretionary lapilli; dolerite, gabbro, leucogabbro, pegmatitic gabbro, granite, and adamellite; xenolithic dolerite/gabbro; andesite, dacite, rhyodacite, rhyolite; granitoids: adamellite, monzogranite, syenogranite, granodiorite, tonalite, granite; granophyre; felsic dykes; and felsic porphyry. They are expressed as granitoid batholiths, komatiite and basalt sheets/lenses, mafic volcanic/volcaniclastic rocks in sheets, sills of dolerite, gabbro, ultramafic rocks, and diorite, dykes of dolerite, gabbro, and felsic rocks, structurally-oriented dolerite dyke swarms, tuff/volcanic breccia/accretionary lapilli in sheets/lenses, sheets of dacite, rhyodacite, rhyolite, and andesite, gabbroic plugs, apophyses, and a variety of host-rock to xenolith relationships. Today, the Pilbara region is arid, hence outcrop is excellent and many of these geological features are well exposed. The diversity of Archaean to Proterozoic igneous rocks in a relatively compact and well-exposed area and qualifies it as a globally unique potential Precambrian igneous-rock geopark.

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1. Introduction

Igneous rocks are varied and complex in composition and occurrence, ranging from the familiar coarse-grained, light-coloured granites and coarse-grained, dark-grey gabbros, to silvery-blue larvikite, to dark-grey, fine-grained basalts, to orbicular granite, to fragmental breccias, amongst many others, and occurring in settings of volcanic terrains to intrusive narrow, sheet-like bodies such as sills and dykes, to intrusive large bosses, to mention a few (Barker, 1983; Bowes, 1989; Hatch, Wells, & Wells, 1972; Lahee, 1961).

Generally, to comprehensively and adequately sample the wide range of igneous rocks, students and geotourists often have to travel to a given continent across various chronostratigraphic units (*i.e.*, geochronologically-varied provinces) and crossing a scattering of geological relationships in widely differing craton and basin settings. For instance, using Australia as an example (Fig. 1) and ordered in age sequence: Streaky Bay provides Proterozoic red granite (Ferris, Gray, & Pain, 1997); Black Hill has Cambrian/Ordovician black gabbro/norite (Cooper, 2019); the Cliefden Caves area has Ordovician andesitic pillow lavas (Packham, 1969; Smith, 1966); Benambra provides a variety of Silurian to Triassic granites, syenites, granodiorites, diorites, and trachyte and rhyolite dykes (Vandenberg et al., 1998); Bathurst has Carboniferous granite batholiths (Joplin, 1931; Vallance, 1969); sea cliffs at Kiama expose Permian latite flood extrusions with explosive contacts with underlying marine sediments (Campbell, Conaghan, & Flood, 2001; Raam, 1969); eastern Tasmania has the World's largest exposure of dolerite intruding as sills (Seymour, Green, & Calver, 2007); a Jurassic diatreme (with brecciation, dykes, contacts relationships, xenoliths and xenocrysts) occurs at Dundas Valley (Wilshire, 1961; Wilshire & Binns, 1961; Semeniuk, 2019); a variety of early Cretaceous volcanic features and spectacular spherulites in rhyolite occur at Mt. Hay/Wycarbah (Bryan & Purdy, 2013); while Mt. Gambier (Sheard, 1995), the Warrumbungle Ranges (Faulks, 1969; Wilkinson, 1969), and the Glasshouse Mountains (Cohen, Withnall, & Vasconcelos, 2013) illustrate Cainozoic trachyte, rhyolite, and basaltic volcanism. In Western Australia (Fig. 1), a land of extensive Precambrian rocks, the Yilgarn Craton exposes mostly granites and dolerite dykes (though Mount Magnet exhibits iconic orbicular granite; Bevan & Bevan, 2009; Brocx & Semeniuk, 2017; and locally there are layered intrusions; Ivanic, Wingate, Kirkland, Van Kranendonk, & Wyche, 2010; Ivanic, 2016), the Kimberley region offers granites, dolerites, basalts, lamproite plugs, and Bunbury and Black Point exhibit extrusive Cretaceous basalt (Geological Survey of Western Australia, 1990).

In contrast to this scattering across Australia of specific igneous rock geology for the purposes of education, geotourism, and research, the Pilbara region in Western Australia within a fairly compact area contains a wide variety of well-exposed igneous rocks, ranging from plutonic batholiths, to shallow-seated intrusions of various modes of emplacement, volcanic extrusions, and

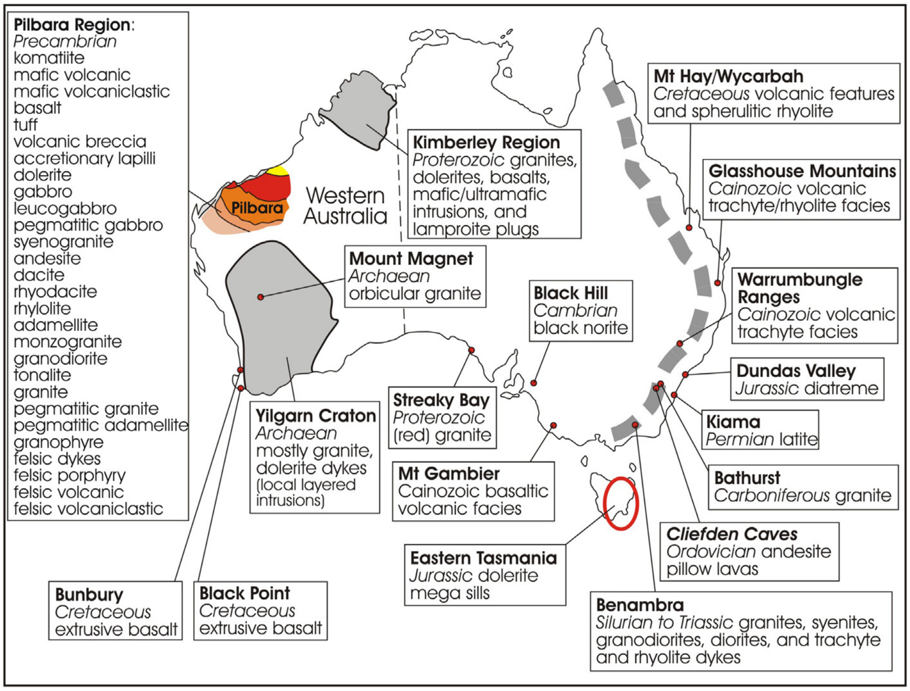

Fig. 1. Map of Australia showing some key occurrences of igneous rock mentioned in the text, their ages, and, for some, their geological setting (this map is not exhaustive but indicative of the range and relative abundance/diversity and spatial scattering, and sometimes isolated occurrences of igneous rock types, and the large distances involved in viewing the full variety of igneous rocks in Australia if there is to be thematic igneous rock geotourism). The dashed grey line indicates the general location of the north-to-south belt of Cainozoic volcanism (Sutherland, 1995) that, in part, defines the eastern highlands of Australia. Note that, in contrast to the other Australian locations, the Pilbara region has a plethora and diversity of igneous rock geology.

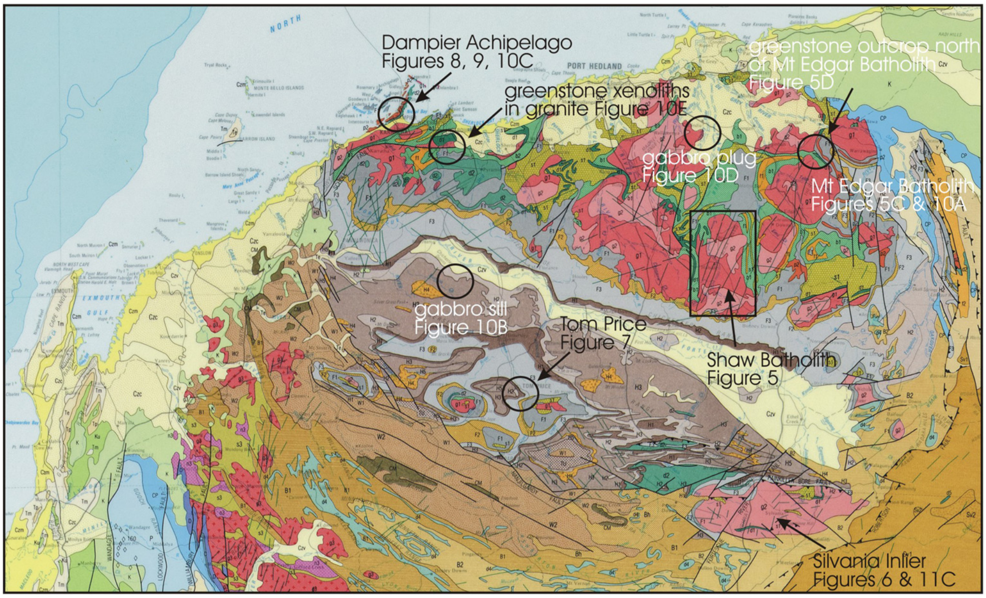

Fig. 2. Geological map of the mid-west of Western Australia focused on the Pilbara region (from Geological Survey of Western Australia, 1988). It shows the extent and complicated stratigraphy of the Pilbara region. Evident are the Archaean granitoid domes and their circumferential greenstones characterising the northern region, and the north-west trending belts of interlayered volcanic rock, sedimentary rock, sills and dykes that characterise the central to southern region. The Pilbara region is defined as the total ensemble of Precambrian rocks comprising the Archaean granite-greenstone complex and the more southerly adjoining Proterozoic sequences. Today, the northern boundary of the Pilbara region is the Canning Basin; its southern boundary is the limit of the outcrop of the Wyloo Group, and its western boundary is largely obscured by Cainozoic cover or is terminated as outcrops at the coast. For a simplified version of this map, refer to Fig. 3. Localities mentioned in the other Figures and in the text are annotated on this map.

flood extrusions. Further, the igneous rock diversity is restricted to the Precambrian. The Pilbara region also is well known to contain the oldest and best-exposed granite-greenstone terrane in Australia. As such, the region is a location in which a wide variety of Archaean to Proterozoic igneous rocks are available for study and geotourism (Fig. 2) in a relatively contained area. Additionally, in terms of Precambrian crustal history and constructional crustal materials, the older parts of the Pilbara successions are essentially built of igneous rocks providing students and geotourists with unparalleled access to Precambrian igneous processes, geochemistry, and history.

What the Pilbara region provides in terms of igneous rocks for the student and geotourist in a relatively compact area of some 500 km $\times$ 500 km is: (1) a variety of igneous rock types from acid through intermediate to ultrabasic/basic rocks (*e.g.*, granite, adamellite, gabbro, dolerite, basalt, komatiite); (2) a variety of settings from deep-seated intrusive massifs to shallow intrusive bodies to extrusive flows and explosive extrusions expressed as batholiths, plugs, sills, dykes, extrusive sheets, volcanoes; (3) a variety of contacts (*e.g.*, chilled margins, apophyses, melted margins, brecciation, stoping); (4) a variety of structures (*e.g.*, breccias, layering, vesicules, pillows, stoping); (5) an age range of igneous rocks from the Archaean to the Proterozoic; and (6) the oldest igneous rocks in Australia, showing the types and evolution of igneous crust in this part of the World in the Precambrian. The Archaean to Proterozoic igneous rocks of the Pilbara region thus can be considered to be a geological jewel as an educational, research, and geotour resource for igneous rocks. Given these attributes, the Pilbara region forms the basis for an excellent geopark for igneous rocks in that there is a plethora of these rocks in a fairly compact area. As an ensemble of igneous rock types, and igneous rock settings, the Pilbara region offers internationally-significant geology as a globally-unique potential geopark and, to date, this aspect of the Pilbara region has not been identified or emphasised.

This paper is structured as follows: (1) geology and chronometric settings of the Pilbara region; (2) the Precambrian stratigraphic framework of the Pilbara region and the variety of igneous rocks and their geological settings; (3) a photographic/diagrammatic essay of igneous rock features in the Pilbara region to showcase some of its interesting, typical, representative, and iconic sites; and (4) discussion: the case for a regional thematic geopark based on igneous rocks in the Pilbara region.

2. Regional geology and chronometric settings of the Pilbara region

There is an abundance of literature on the geology and geochronometry of the Pilbara region and, in addition to those cited in the text, the reader is referred to Geological Survey of Western Australia (1990), Myers (1990a, 1990b), Thorne (1990), Trendall (1990a, 1990b), and Tyler (1990a, 1990b) for key references and history of geological research to provide a perspective of the scope, breadth, and depth of geological information on this area. However, for purposes of this paper, focused mainly on the igneous rocks of the area, the geology of the Pilbara region is simplified in Fig. 3 to provide the essentials of its regional geological

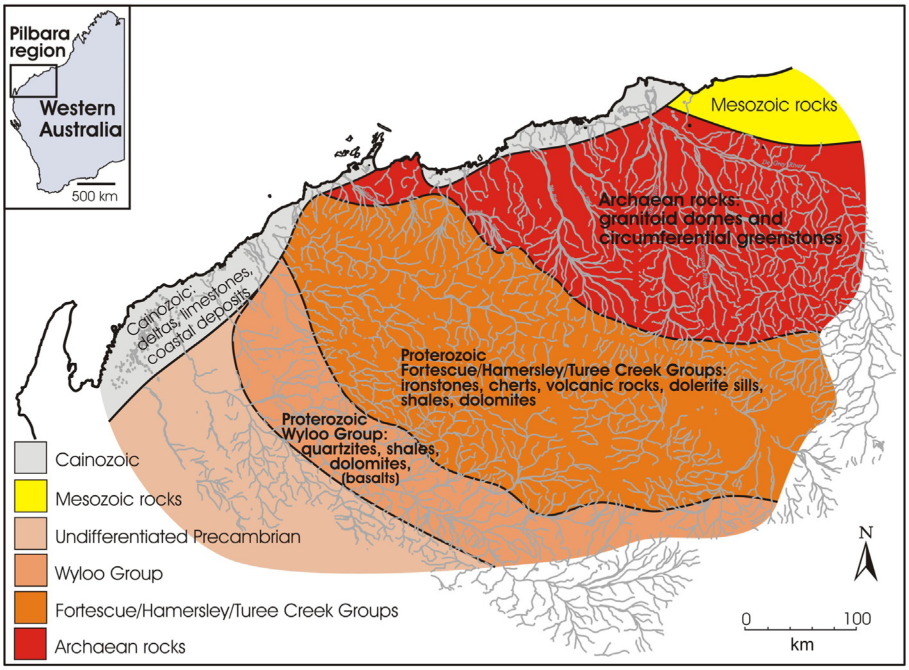

Fig. 3. Simplified Precambrian geological framework (based on Fig. 2, and modified after Brocx & Semeniuk, 2018) showing the disposition of the Archaean granite-greenstone terrane, and the occurrence of the younging sequence of the north-west trending belts of the Fortescue, Hamersley, Turee Creek, and Wyloo groups; the background line work shows the dense drainage patterns that characterise the dissected uplands of the Pilbara region.

and chronometric setting – this map shows the distinctive four-fold Precambrian geological framework that is host to the various igneous rocks.

The igneous rocks in the Pilbara region can be assigned to three main settings (Fig. 3): those occurring in a northern region as an Archaean granitoid-and-greenstones complex (the Pilbara Craton; 3.6–2.7 Ga; Blake & McNaughton, 1984) with granitoids in domes separated by greenstone in inter-dome structures; those in the central region within the layered Proterozoic sequences (2.5–1.8 Ga) comprising volcanic rock, volcaniclastic rock, ironstone, chert, dolomite, shale, and intrusive dolerite sills and cross-cutting dolerite dykes assigned to the Fortescue, Hamersley, and Turee Creek groups; and those to the south comprising Proterozoic sequences of shale, dolomite, and chert, assigned to the Wyloo Group, with isolated granitic batholiths occurring as later intrusions.

3. The Precambrian stratigraphic framework of the Pilbara region and the variety of igneous rocks and their geological settings

The rock sequences, commencing with the northerly Archaean granite-greenstone form a succession of southward younging and lithologically-distinct suites of Proterozoic volcanic and sedimentary rocks (in turn, the Fortescue, Hamersley, Turee Creek, and Wyloo groups). As the Proterozoic sequences young southwards, the occurrence of volcanic rock also becomes less frequent. Lithologies in the region and the igneous rocks in the various formally named sequences chronogeologically are summarised in Fig. 3. Note, however, that some of the younger dyke-, sill-, and plug-intrusions, while they are Proterozoic in age, are regionally intrusive and, as such, intrude Archaean rocks as well as Proterozoic rocks (which effectively increase the diversity of igneous rock types in the Archaean terranes). The rock type 'laminated ironstone' is commonly termed 'banded iron formation' and 'BIF' by geologists in Western Australia (Geological Survey of Western Australia, 1990).

The sequences are described in some detail below.

3.1. The granite-greenstone terrane (the Pilbara Craton)

The Pilbara Craton, an Archaean granite-and-greenstone complex exposed over 60,0000 km^2 of the northern Pilbara (Hickman, 1984), contains the oldest and best-exposed granite-and-greenstone terrane in Australia. The greenstones include metamorphosed basalt, sandstone, shale, chert, banded ironstones, and felsic volcanic rocks, as well as mafic-ultramafic schist. Granitoid rocks constitute 60% of the terrain, generally occupying anticlinal domes, up to 120 km across, separated by greenstones in synclinal structures (Fig. 5). The important granitoids are comprised of adamellite, monzogranite, syenogranite, granodiorite, and migmatite.

Granitic batholiths, or in the terms of some authors, "granitoid complexes", are conspicuous in the Pilbara Craton (Bettenay et al., 1981; Bickle, Bettenay, Boulter, Groves, & Morant, 1980; Hickman, 1981, 1983, 1984) as evident on aerial photographs

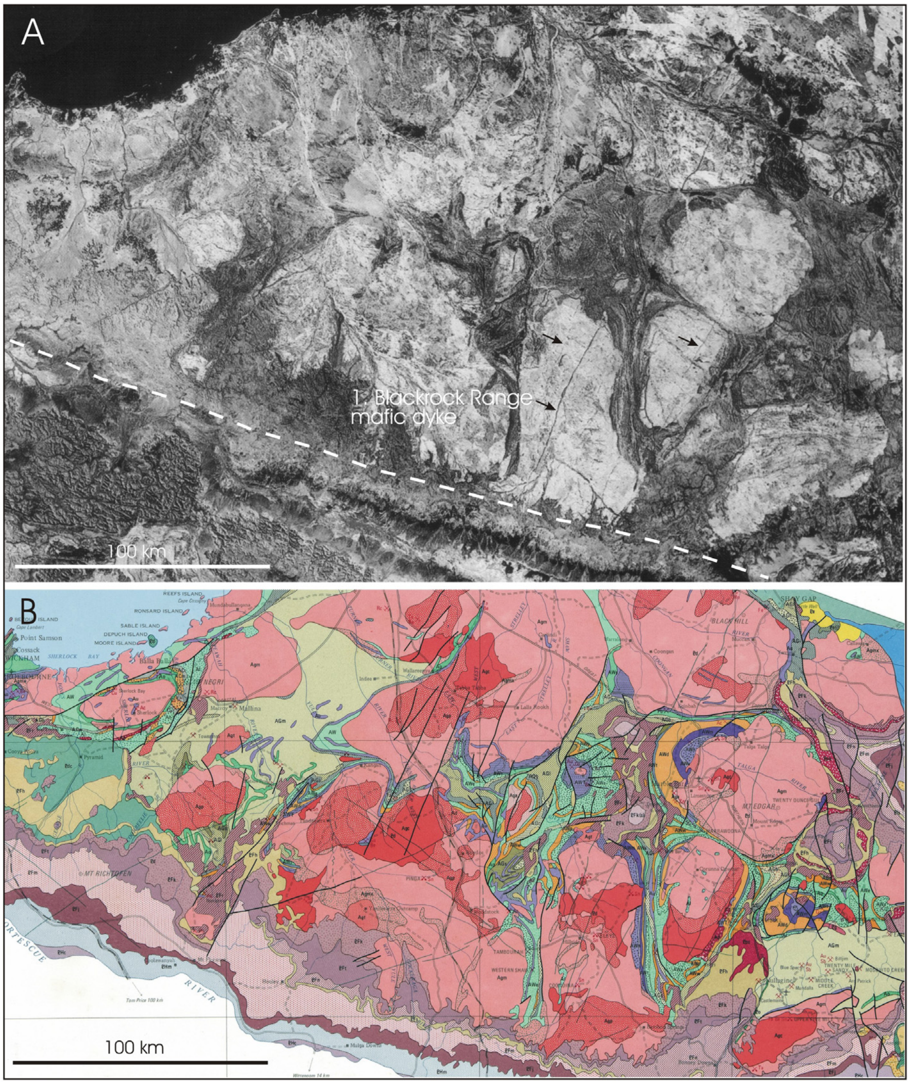

Fig. 4. A. Satellite image of the Archaean granite-greenstone terrane – the light grey oval to quadrat areas are domal granitoids and these are surrounded by the greenstones that are appear in the image as alternating dark grey/light grey inter-dome bands. The sharp boundary between the granite-greenstone terrane and the northwest-trending layered Proterozoic sequences is marked in the image by the white dashed line. Some dolerite dykes (dark lines) cutting across the granite domes are arrowed – the large dyke comprising Blackrock Range is numbered as (1). B. Geological map of the Archaean granite-greenstone terrane – the granitoid bodies are pink, and the greenstones are outlined by the striped many-toned patterns between the domal granites (map from Geological Survey of Western Australia, 1988; for interpretation of the references to colours in this figure, the reader is referred to the web version of Geological Survey of Western Australia, 1988).

(Fig. 4). These batholiths, or the granitoid complexes, form ovoid to quadrat bodies up to 120 km across in the northern Pilbara granite-greenstone terrain. The best exposures are the Shaw, Yule, Mount Edgar, and Corunna Downs Batholiths, and these exhibit wide variations in rock type and deformation style, and exemplify the typical batholiths in the region. Three main types of rocks occur within the granitoid complexes, ordered here in terms of time of emplacement: (1) early gneiss and migmatite; (2) foliated porphyritic granitoid (which is dominant); and (3) massive post-tectonic granitoid.

Areas of early gneiss and migmatite are closely associated with intercalations of greenstones of pelitic and feldspathic schist, metajaspilite, minor amounts of calc-silicates, ultramafic schist, and amphibolite that is derived from both intrusive and extrusive mafic magmas. These rocks are highly deformed and attenuated along with the adjacent granitoid body (now composed of biotite-granodiorite gneiss, banded leucogneiss, and banded hornblende gneiss; Bettenay et al., 1981). Tonalite also is abundant in these older gneissic granitoids. Foliated, porphyritic and non-porphyritic monzogranite and granodiorite comprise the bulk of the granitoids. Syenogranite is more common in the younger, generally undeformed intrusions associated with mineralisation and late pegmatites (Blockley, 1980).

Contacts of post-tectonic granitoids with surrounding country rocks clearly show cross-cutting intrusive relationships, and the foliated monzogranite and granodiorite are viewed as magmatic intrusions (Hickman, 1984). The older, deformed granitoids have

Table 1
Stratigraphic and lithologic subdivisions of the Archaean greenstones (after Hickman, 1981, 1983).

Groups, subgroups, and formations	Main lithology	Thickness (m)
Negri Volcanics	Basalt and andesite	200
Louden Volcanics	Basalt and ultramafic rocks	1000
Whim Creek Group		
Rushall Slate	Slate, minor tuff	200
Mons Cupri Volcanics	Felsic volcanic rocks	500
Warambie Basalt	Vesicular basalt	200
Gorge Creek Group		
Mosquito Creek Formation	Psammitic-pelitic schist	5000
Lalla Rookh Sandstone	Sandstone and conglomerate	3000
Honeyeater Basalt	Basalt (pillowed)	1000
Soanesville Subgroup		
Cleaverville Formation	Laminated ironstone	1000
Charteris Basalt	Basalt (and dolerite)	1000
Corboy Formation	Metasediments	1600
Warrawoona Group		
Wyman Formation	Rhyolite	1000
Salgash Subgroup		
Euro Basalt	Basalt (and komatiite)	2000
Panorama Formation	Felsic volcanic rocks	1000
Apex Basalt	Basalt (and komatiite)	2000
Towers Formation	Chert and basalt	500
Duffer Formation	Felsic volcanic rocks	5000
Talga Talga Subgroup		
Mount Ada Basalt	Basalt	2000
McPhee Formation	Carbonate, schist, and chert	100
North Star Basalt	Basalt	2000

foliated/sheared (concordant) contacts against gneiss and greenstone sequences, and primary relationships are obliterated. Intrusions of granitoids at 3.45–3.55 Ga are regarded as contemporaneous with calc-alkaline volcanism, and the deformation of Pilbara greenstones at about 3.0 Ga may have been caused by the rise of substantial masses of granitoid, by solid-state diapirism, through the greenstone pile (Hickman, 1981, 1983, 1984). Foliated granodiorite, along with subordinate monzogranite, tonalite, and quartz diorite in the north of the Shaw Batholith, on the other hand, are chemically and isotopically (3.5 Ga) similar to strongly deformed gneiss in the south-west of the granitoid complex, implying the latter gneiss was derived from foliated granodiorite by tectonic processes (Bickle et al., 1983, 1985).

The granitic batholiths generally occupy anticlinal domes, whereas the greenstones (referred to the Pilbara Supergroup) occur in adjacent synclinal structures. Within the granitoid complexes, the gneiss and intercalated greenstones occupy tight synclinal structures, with the structures developing during an extended period of solid-state diapirism (Hickman, 1975, 1984). Studies on the Shaw Batholith suggest that a complex structural history for the greenstone intercalations and gneiss, related to the overall development of the granitoid complex involving thrusting and recumbent folding of the early greenstones and granitoid intrusions (Bettenay et al., 1981; Bickle et al., 1980, 1985).

Ages of the greenstone sequence show that the primary rocks accumulated between 3.6 Ga and 2.8 Ga (Blake & McNaughton, 1984). The maximum thickness of the succession is about 15,000 m, though its basement is unknown. The regional geometry of the oldest rocks is regarded as tabular, although sketches showing stages in the evolution of the greenstones imply more complexity (Hickman, 1981, 1983). All the Archaean greenstones of the Pilbara region were grouped by Hickman (1983) as the Pilbara Supergroup. The main stratigraphic units of the Pilbara Supergroup are described below in terms of main lithologies and thickness (Table 1). In this supergroup, the igneous rocks as part of the stratigraphic sequence include are basalt and ultramafic rocks (*e.g.*, komatiite), dolerite, andesite, and felsic volcanic rock.

Table 2
lithologies and igneous rocks in the various sequences and formations with their characteristic igneous rock types in the Pilbara region (age determinations generalised from Arndt, Nelson, Compston, Trendall, and Thorne, 1991 and Geoscience Australia and Australian Stratigraphy Commission, 2019).

Wyloo Group	Sandstone, mudstone, conglomerate, siltstone, dolostone, mafic and felsic volcanic and volcaniclastic rocks, laminated ironstone, chert; thickness 12,000 m; age 2446–1800 Ma
Turee Creek Group	Sandstone, siltstone, dolostone and diamictite; thickness 5000 m; age 2208 Ma
Hamersley Group	Chert, laminated ironstone, jaspilite, dolomite, mudstone, siltstone; thickness 2500 m; age 2600–2440 Ma
Fortescue Group	Mafic volcanic rocks - basaltic and andesitic lavas, siliciclastic sedimentary rocks, chert, minor pyroclastic rocks and carbonates; thickness 6500 m; age 2775–2690 Ma (Arndt et al., 1991)
Archaean granite-greenstone	Various granitoids and greenstones

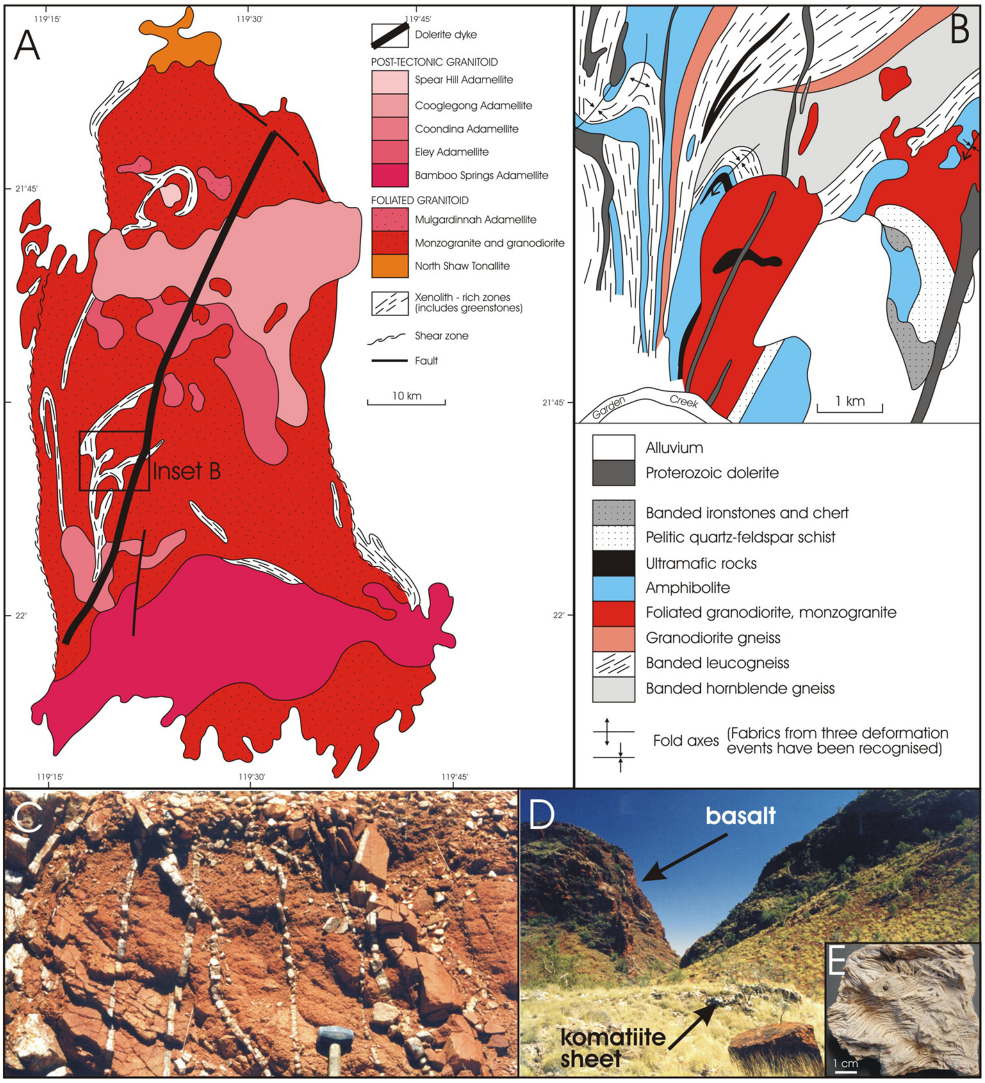

Fig. 5. A. Geological map of the Archaean Shaw Batholith (see Fig. 2 for location) showing range of lithologies from adamellite, to monzogranite, to granodiorite, to tonalite; occurrences of xenolith-rich zones are also mapped; the dolerite dyke crossing the granitoid is the Blackrock Range dolerite shown in Fig. 11B. Map modified from Geological Survey of Western Australia (1990). B. Geological map of an enclave of greenstones amongst the granitoids. Map modified from Geological Survey of Western Australia (1990). C. *In situ* adamellite with prominent quartz veining. D. Outcrop of komatiite (foot of the hill) and basalt (cliff outcrop) in greenstones of the granite-greenstone terrane north of the Mt. Edgar Batholith (locality shown in Fig. 2); the komatiite commonly has spinifex texture, and now is dolomitised; *cf.* Shore and Fowler (1999) and Faure, Arndt, and Libourel (2006). E. Close-up of dolomitised komatiite in (D) showing spinifex texture.

Table 3
The later intrusions in the Pilbara region.

Type of intrusion	Field description	Main occurrence
Dolerite/gabbroic dykes	Recessively weathering to prominently outcropping depending on weathering history of country rock setting; metres wide to several metres wide to ~10 m wide, of dolerite or gabbro	Dolerite dykes common in many areas of the Proterozoic sequences, and granite-greenstone terrane; gabbroic dykes intrude the granite-greenstone terrane
Small to medium dolerite sills	Layer-parallel sills, metres to tens of metres thick, intrude into proterozoic hamersley group	Dolerite sills common in the ironstone formations in many areas of the hamersley group
Large gabbroic/dolerite sill	Large sill, 100 s of metres thick, intruding along shear within the Proterozoic greenstone sequences	Centred on and comprising the landscape of the Dampier Archipelago
Doleritic to gabbroic plugs	Small body tens of metres diameter, intruding into Archaean granitic rocks of the granite-greenstone terrane	Located in the granitic batholiths between Port Hedland and Roebourne
Young granite batholiths	Large Proterozoic granitic batholiths, intruding the younger part of the Proterozoic sequence	South-eastern Pilbara region

Table 4
Variety of igneous rocks in the Pilbara region (from ultramafic to mafic to felsic).

- Komatiite
- Mafic volcanic/volcaniclastic rocks
- Basalt
- Tuff/volcanic breccia
- Accretionary lapilli
- Dolerite, gabbro, leucogabbro
- Pegmatitic gabbro
- Xenolithic dolerite/gabbro
- Andesite, dacite, rhylolite, rhyodacite
- Granitoids: adamellite, monzogranite, syenogranite, granodiorite, tonalite, granite
- Pegmatitic granite, adamellite, monzogranite
- Granophyre
- Felsic dykes
- Felsic porphyry
- Felsic volcanic/volcaniclastic rocks

3.2. The layered Proterozoic sequences

The layered Proterozoic sequences comprise supracrustal rocks up to 10,000 m thick, and cropping out over an area of 100,000 km^2 south of the Archaean granite-greenstone terrane (Fig. 3). The stratigraphy comprises a range of layer-parallel sequences of volcanic rocks, shales, cherts, banded ironstones, and dolomites, with volcanic rocks occurring towards the base of the sequence, ironstone, dolomite and shale in the middle of the Proterozoic sequence, and shale, sandstones and dolomite towards the top of the sequence. The rocks are assigned to four Groups as follows (Fig. 3; and MacLeod et al., 1966): (1) the Wyloo Group (top); (2) the Turee Creek Group; (3) the Hamersley Group; and (4) the Fortescue Group (base). The Fortescue Group, with a total thickness of 6000 m, comprises 60% of the outcrop of the Proterozoic sequence, and is composed of mafic volcanic rocks and volcaniclastic rocks, some subordinate felsic rocks, and sandstone, conglomerate, and dolomite. The Hamersley Group, with a total thickness of 2500 m, comprises nearly 30% of the outcrop of the Proterozoic sequence, and is characterised by banded ironstones, shale, and dolomite. A significant thickness of the Hamersley Group, totalling about 1000 m is composed of intrusive sills (see later). The Turee Creek Group, with a total maximum local thickness of 1200 m, comprising about 10% of the sequence, crops out only locally, and is composed of fine grained the Proterozoic sequences are described below in terms of main lithologies, thickness, (Table 2) and ages.

3.3. Later intrusions

In the Pilbara region the entire succession of the Archaean to Proterozoic craton and Proterozoic layered sequence is intruded by younger igneous rocks. These include dolerite and gabbroic dykes, quartz dykes, small to medium sized dolerite sills, large scale gabbroic to dolerite sills, dolerite plugs, and young granitic batholiths (Figs. 5A, 7C, 9C, 10B, C). The occurrences of these later intrusions are detailed in Table 3 below.

3.4. The variety of igneous rocks and their modes of occurrence in the Pilbara region

In the Pilbara region, there some 28 types of igneous rocks, as listed in Table 3 below. Table 4 lists the rocks in order from ultramafic to felsic. Geologically, in terms of geometry and emplacement, they occur as batholiths, sills, dykes, (surface) sheet

Table 5
The various igneous rock bodies.

- Granitoid batholiths,
- Komatiite and basalt sheets and lenses in the greenstones,
- Mafic volcanic/volcaniclastic rocks in sheets in the Proterozoic sequences,
- Thick dolerite sills, gabbro sills, ultramafic sills in the Proterozoic sequences,
- Dolerite dykes, gabbro dykes in the Proterozoic sequences,
- Structurally-oriented dolerite dyke swarms in all rock sequences,
- Gabbroic plugs,
- Felsic dykes,
- diorite sills,
- Tuff/volcanic breccia/accretionary lapilli in sheets and lenses in Proterozoic sequences,
- Rhyolite, dacite, rhyodacite, andesite sheets,
- A variety of host-rock to xenolithic relationships in all rock sequences
- Apophyses of basaltic rock intruding the country rock
- Apophyses of felsic rock intruding the country rock
- Pegmatitic granite gabbro as vein structures or base of intrusion

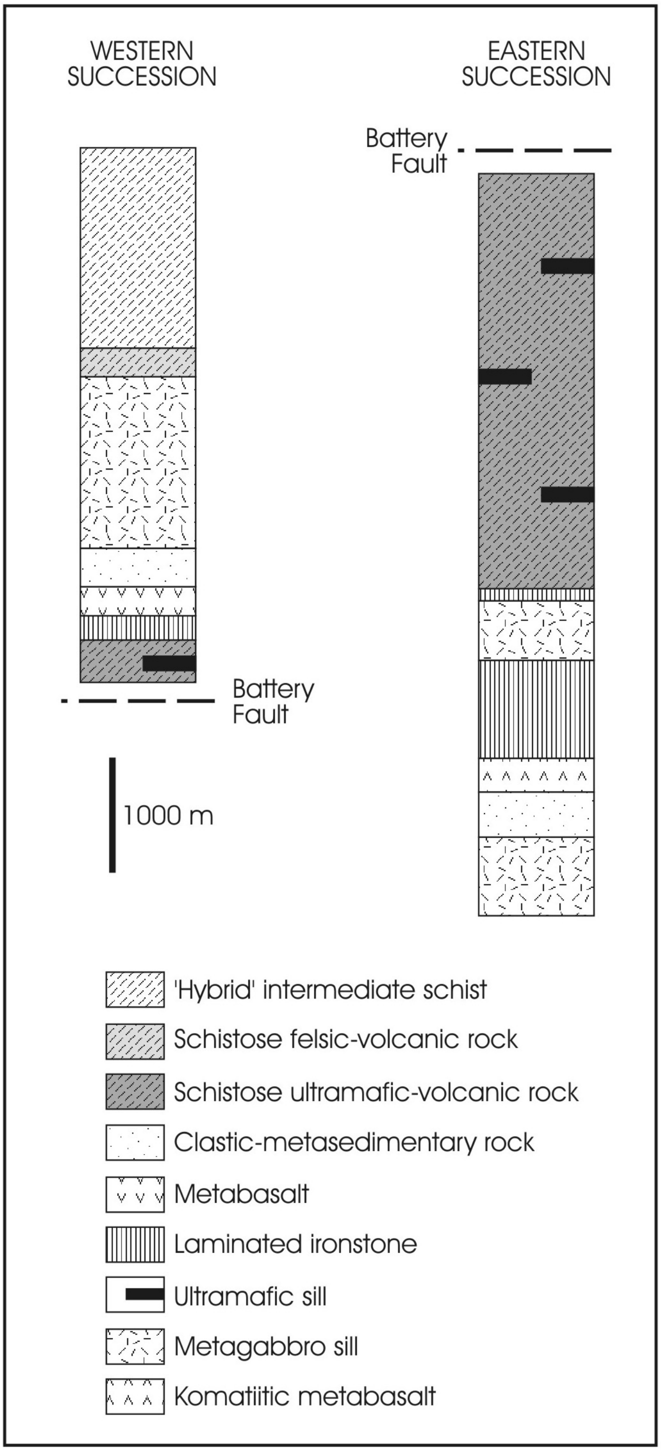

Fig. 6. Stratigraphic columns in greenstones within the Sylvia granite-greenstone inlier (for location see Fig. 2) showing the range of igneous rock and sedimentary rock interlayers. Map modified from Geological Survey of Western Australia (1990).

and lensoid extrusions, plugs, and apophyses, as listed in Table 5 below. For Australia, this diversity of igneous rocks in a relatively compact area is not surprising since the time span of igneous activity is 1.8 Ga, time enough to undergo crustal evolution develop varying magma types, whereas much of the rest of Australia has igneous activity mainly in the Phanerozoic eon.

4. Photographic/diagrammatic essay of igneous rock features in the Pilbara region

This section of the paper is a photographic/diagrammatic essay of various key igneous rock features in the Pilbara region with Figure captions and map legends carrying the weight of descriptions. These key features are illustrated not to provide a geotour package or geotrails but only to indicate the range and quality of igneous rocks available in the region that lend themselves to Science, Education, and Geotours. Given the description of the geological framework wherein the igneous rocks are lodged, and also the regional setting of the various rocks types in the Pilbara region, future geotour operators, students, and researchers can design their own geosite stops, and geotrails based on quality of outcrops and accessibility. Details for any number of geotrails for geotours that cover the quality geology are outside the scope of this paper, and will be presented in later papers focused on geotourism.

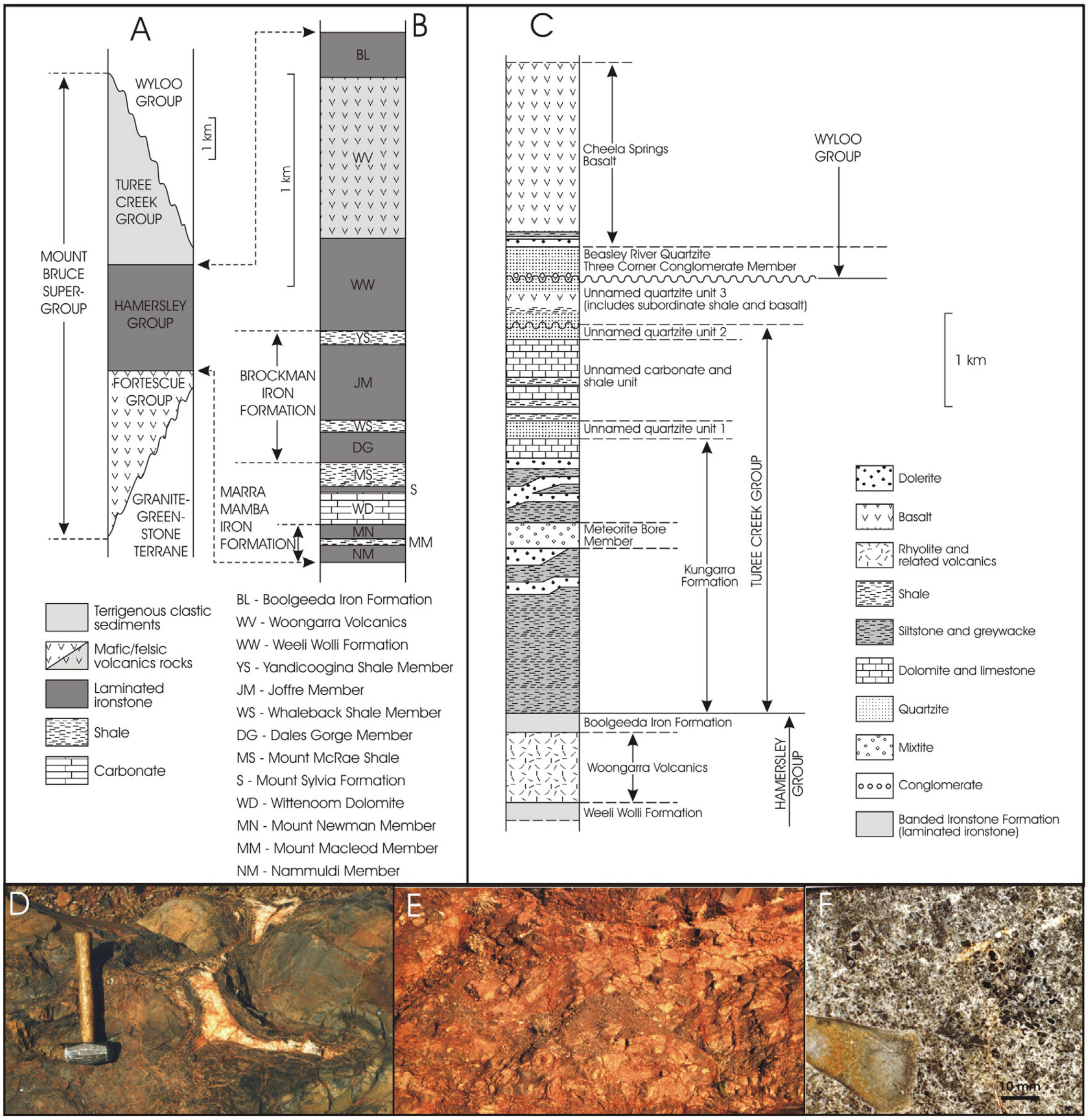

Fig. 7. A, B & C. Stratigraphic columns in the Proterozoic sequences of Fortescue, Hamersley, Turee Creek, and Wyloo groups south of the Archaean granite-greenstone terrane (for geological setting location see Fig. 3) showing the range of igneous rock and sedimentary rock interlayers (stratigraphic columns modified from Geological Survey of Western Australia, 1990). D. Pillow-lava structures in basalt near Tom Price (for location see Fig. 2). E. Brecciated lower part of basalt sheet near Tom Price (for location see Fig. 2). E. Polished slab of xenolithic accretionary lapilli, near Tom Price (for location see Fig. 2).

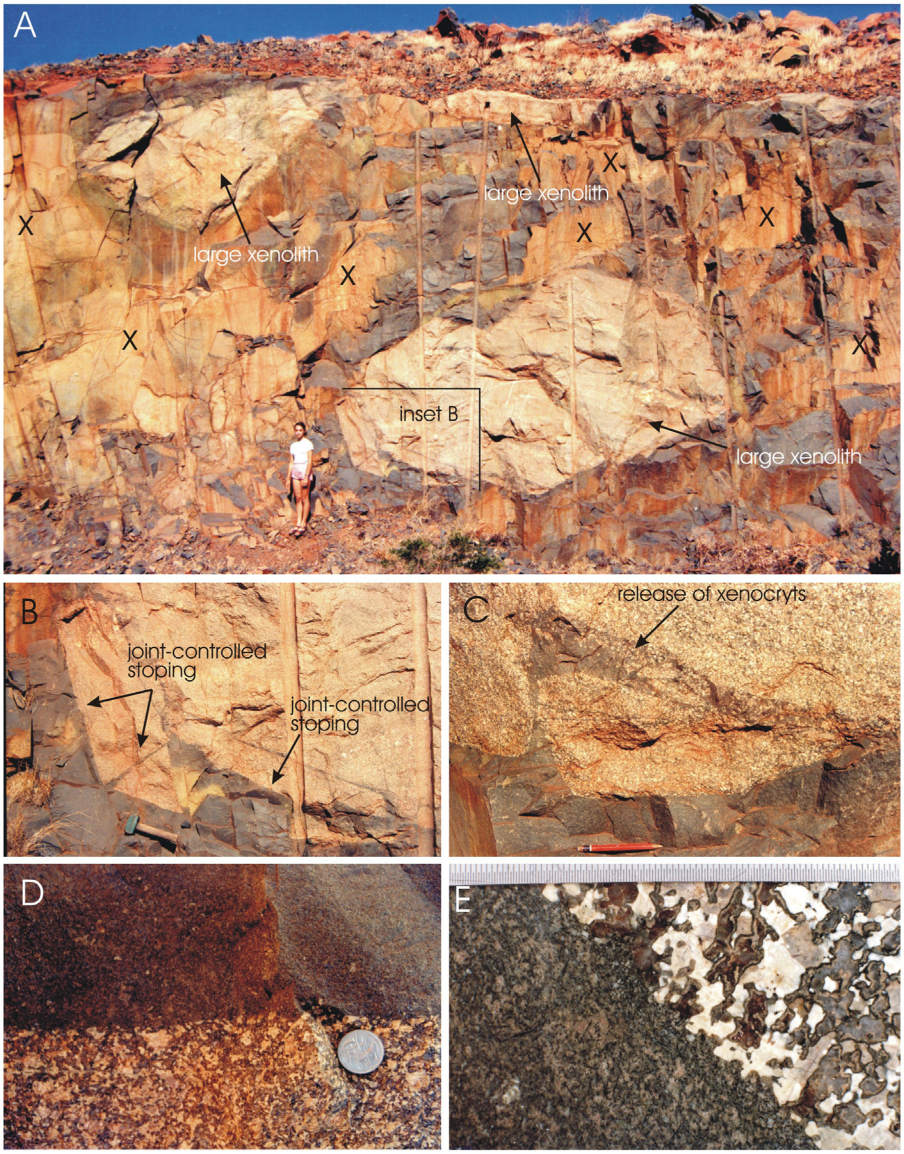

Fig. 8. Proterozoic dolerite/gabbro contact with Archaean granite in the Dampier Archipelago (for location see Fig. 2). A. Three large granite xenoliths (collapsed *via* stoping from the host rock granite body into the mafic magma chamber) are arrowed; the overall shape of the central granite xenolith is controlled by the conjugate joint patterns in the granite; flat areas marked by 'x' are Fe-stained joint surfaces that, in this image, superficially resemble the appearance of granite; the location of inset B is shown. Vertical lines are drill holes. B. Joint control (arrows) of further stoping along the margin of the xenolith. C. Melting by the dolerite magma of the granite has preferentially melted the quartz leaving feldspar crystals to be incorporated into the mafic melt; the xenocrysts are arrowed. D. Sharp contact between dolerite (above) and granite (below) with high-temperature melt creating partial melt textures in the granite (*cf.* Petcovic & Grunder, 2003). E. Gradational contact between dolerite (left) and granite (right) with high-temperature melt invading the granite by preferentially melting the quartz in the granite *via* amoeboid to reticulate invasion fronts.

The photographic/diagrammatic essay presented in Figs. 4–11 covers, in decreasing age order, the following areas and rock suites:

1. Granite and greenstones in the granitoid-greenstone terrane (Figs. 4, 5, 6, 10A);
2. Komatiite and basalt in the greenstones of the granitoid-greenstone terrane (Fig. 5D, E);
3. Stratigraphic columns in greenstones of the granitoid-greenstone terrane (legend to Figs. 5B, and 6);
4. Xenolithic margin of intrusion in the granitoid-greenstone terrane (Figs. 5A, 10D);
5. Gabbro plug in the granitoid-greenstone terrane (Fig. 10B);
6. Layered volcanic/volcaniclastic rocks, 'sedimentary rocks', dolerite sills, and dolerite dykes in the Proterozoic sequences (Fig. 7);
7. Megascale gabbro sill in the layered Proterozoic sequences (Fig. 10C);

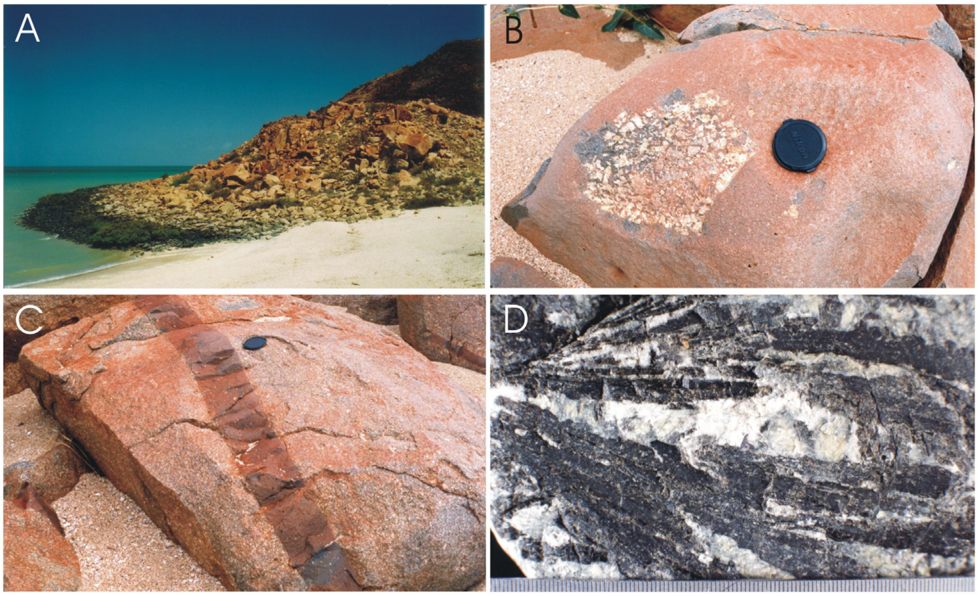

Fig. 9. Features of the Proterozoic dolerite/gabbro contact with Archaean granite in the Dampier Archipelago (for location see Fig. 2). A. Overview of contact between granite (lower light brown rocks) and dolerite/gabbro (upper black rocks) in a coastal cliff; tidal zone cut into the shore is bouldery (arrow 1), and the fringe of dark rock (arrow 2) in the lower tidal zone is algae-covered pebbles/boulders. B. Xenolith of granite with reaction rim (camera lens cap for scale). C. Dyke of basalt intruding the dolerite (camera lens cap for scale). D. Pegmatitic gabbroic in lower part of gabbro intrusion showing fan array of prismatic pyroxene crystals (scale along lower edge of image is in millimetres).

8. Features of the dolerite/gabbro sill in granite in the granitoid-greenstone terrane in the Dampier Archipelago (Figs. 8, 9, 10E);
9. Archaean to Proterozoic mafic dyke swarms (Fig. 11).

The Pilbara region has undergone low-grade metamorphism and consequently many igneous in most localities have good preservation of macro-, *meso*, and microscale structures and textures as evident in the images in Figs. 5E, 7D, E, F, 8, 9B, D, & 10E. In addition, as mentioned above, crystal zoning, crystal resorption, development of xenocrysts, amygdules (former vesicular structures), and xenolith reaction rims, amongst others, are well preserved.

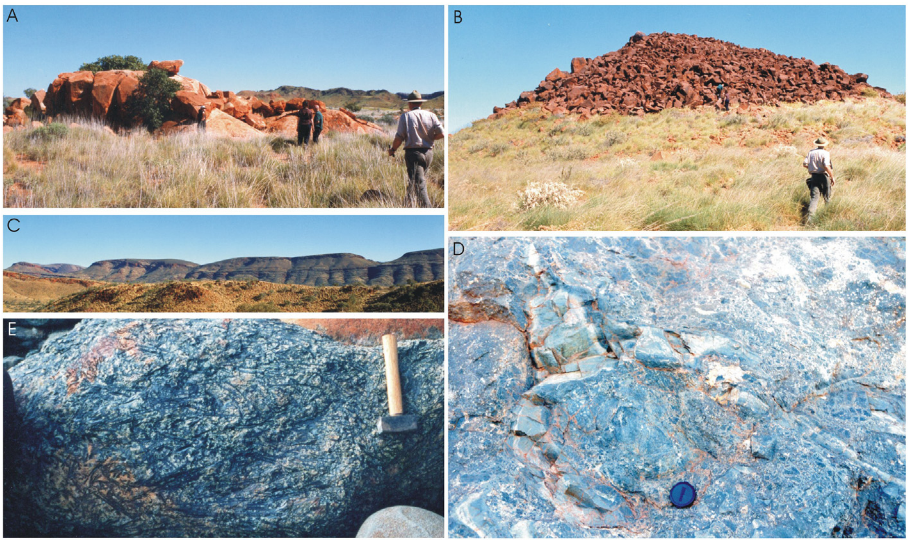

Fig. 10. Miscellaneous sites of Archaean to Proterozoic igneous rocks (sites shown in Fig. 2). A. Outcrop of Archaean adamellite in the Mt. Edgar Batholith. B. Outcrop of a gabbro plug. C. Extensive hill-capping outcrop of gabbro sill (the band of rock at the top of the hill in the far background). D. Xenoliths on greenstone along the margin of a granitoid intrusion (camera lens cap for scale). E. Pegmatitic gabbro in the Dampier Archipelago showing coarse crystals of pyroxene in fan-like (radiating) clusters.

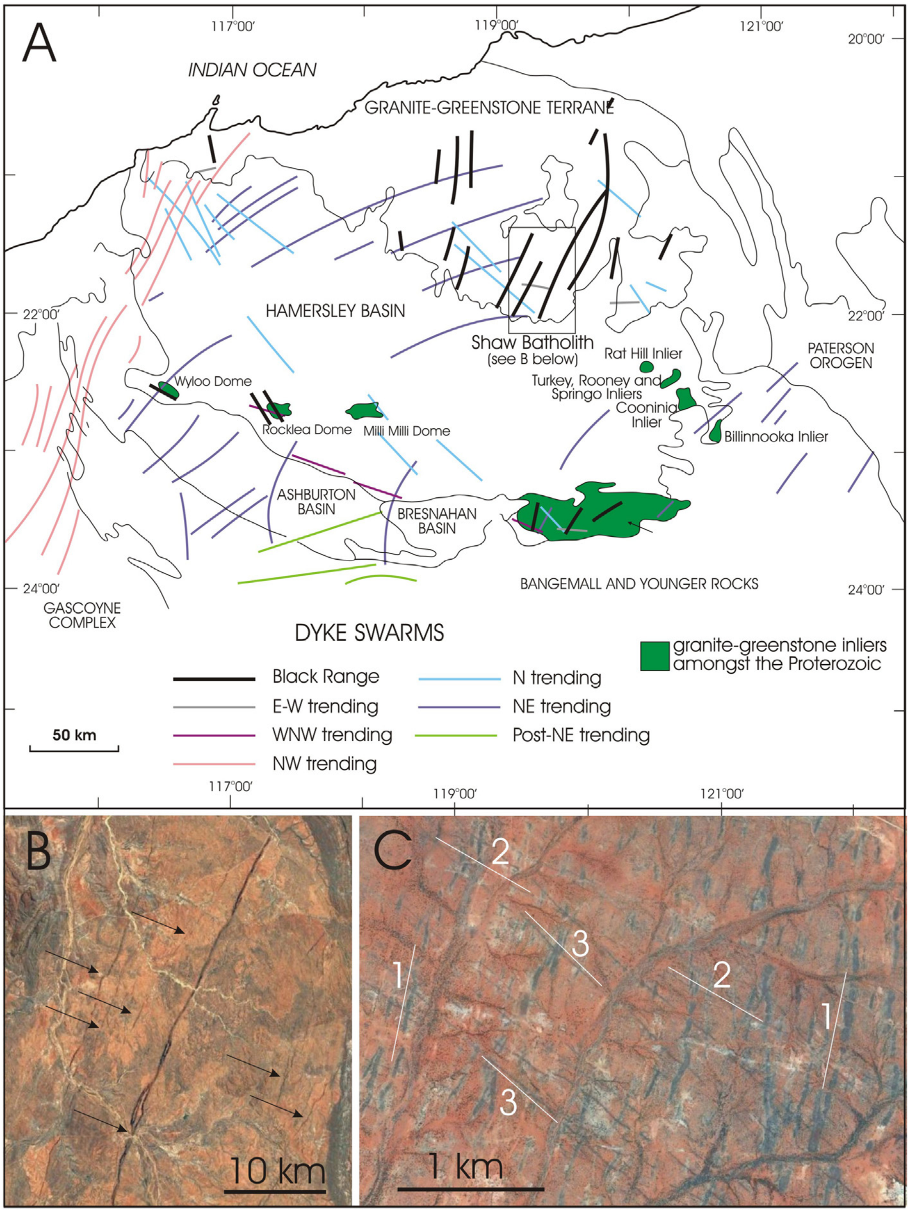

Fig. 11. Archaean to Proterozoic mafic dyke swarms. A. Various generations of mafic dyke swarms in the Pilbara region (map modified from Geological Survey of Western Australia, 1990). B. Various mafic dyke swarms (arrows) cutting across the Shaw Batholith. C. Three generations of mafic dyke swarms in the Sylvia Inlier (see Fig. 2 for location of Sylvia Inlier); selected dykes of each generation of dyke intrusion are bordered by a white line and numbered 1, 2, 3 to illustrate the trend of a given swarm.

5. Discussion and conclusions: the Pilbara region suite of igneous rocks as a geopark

A geopark is a unified area that advances the protection and use of geological heritage in a sustainable way, and promotes the economic well-being of the people who live there (McKeever & Zouros, 2005). Geoparks promote the holistic concept of protection, education and sustainable development. Geoparks often combine an aggregate of sites of geoheritage significance such that they provide geological information informing the public, geotourist, and students about Earth processes and products with signposted geosites, and/or educational localities along geotrails. A common feature of a geopark is that they are diverse and offer a range of geological features in the one area. For example, the English Riviera UNESCO Global Geopark in the United Kingdom provides geosites focused on palaeontology, coastal geomorphology, Devonian stratigraphy, volcanic rocks, palaeo-sedimentology, minerals, and Quaternary cave fauna (Braithwaite, 1967; British Geological Survey, 2004; Floyd, Exley, & Styles, 1993), and the North West Highlands Geopark in Scotland containing the some of the Archaean oldest rocks in Europe, and other notable features, such as the Moine Thrust Belt, Smoo Cave, and a variety of sedimentary, and metamorphic rocks (Dryburgh, Ross, & Thompson, 2014; Elliott & Johnson, 1980).

While geoparks commonly are geologically diverse illustrating the geodiversity of a given region, often they can be thematic. Geoparks based on karst and caves exemplify this (*cf.* Ruban, 2018; Zhizhong, Xun, Changzing, Xiaohong, & Xiaoning, 2015). The Marble Arch Caves UNESCO Global Geopark in Ireland and United Kingdom of Great Britain and Northern Ireland is an example (Jones, Burns, Fogg, & Kelly, 1997; Zouros, 2004) - though there are other aspects of geology in this geopark, the focus is on caves. Other geoparks focused on karst and caves include the Zhijindong Cave Geopark, Guizhou Province in China, with a focus on caves, gorges, natural bridges and sinkholes (Wei, Chen, Luo, He, & Tan, 2016), the Dolomite Karst Landscape of Suiyang Geopark, also in the Guizhou Province, as an example of dolomite karst landscape system with the longest cave in Asia and the longest dolomite cave in the world (Wei et al., 2018), the various caves in Bulgaria (Beron, Saaliev, & Jalov, 2006), and Dong Van Karst Plateau UNESCO Global Geopark in Viet Nam (Ha et al., 2013).

The Pilbara region of Western Australia geologically is globally unique, recording a younging southward crustal history of Precambrian igneous activity, sedimentation, tectonics, metamorphism, and evidence of early life from the Archaean to Proterozoic. As such, it is geologically diverse. Today, the Pilbara region is arid, hence outcrop is excellent and many of the geological features are well exposed. In this diversity of geology the igneous rocks are variable in age, rock suites, and mode of occurrence and that, throughout the Precambrian, record varying igneous rock activity.

We make the case for a regional thematic geopark specifically based on igneous rocks in this region. The proposed Pilbara Igneous Rock Geopark is unique in that it offers, within a relatively compact area, a wide diversity of Archaean to Proterozoic igneous rocks (from 3.6 Ga to 1.8 Ga in age) showing much lithological variation, structural/emplacement settings, and contact relationships. Specifically, the igneous rocks in the Pilbara region show a plethora of igneous features useful for Science, Education and Geotours from the large scale (in rock relationships and structural setting; various lithologies; layered intrusions with vertical grading in crystal sizes and/or composition; size of sills, dykes, and batholiths; crossing-cutting dykes), to medium scale (stoping; joint-controlled stoping; abundance of xenoliths along intrusion margins; basal lava brecciation; margin melting), and small- to microscale (crystal zoning; crystal resorption; development of xenocrysts; amygdules; xenolith reaction rims; lapilli and accretionary lapilli). Moreover, regionally, these rocks record a southward younging sequence of igneous rock emplacement from the Archaean to Proterozoic and with changes in magma compositions.

Igneous activity begins in the Archaean with mafic and ultramafic volcanism (now greenstones, *e.g.*, metamorphosed basalt, komatiites) alternating with sedimentation (shale, chert, ironstones), and then granitoid cratonisation (*e.g.*, monzogranite, adamellite, syenogranite). This was followed by Proterozoic volcanic crustal accretion with mafic volcanic and volcaniclastic rocks, and then by dolerite and gabbro sill and dyke intrusions, ending with isolated granite batholithic intrusions.

The igneous rocks in the Pilbara thus provide a unique window into Precambrian crust evolution and styles of igneous activity with magma composition and mode of igneous expression determined by age and geological setting. The diverse range of igneous rocks and mode of occurrence in the Pilbara region, from large scale to the microscale, thus provides insights into crust evolution and mechanisms of crust development during the Precambrian and into structural response of the crust to tectonism. For Science, Education, and Geotourism, the Pilbara region presents a wide expression of Precambrian igneous rocks in terms of lithology, mode of occurrence, and relationships. As such the region provides an excellent World-class classroom to investigate and explore igneous rocks in a younging sequence in the Precambrian.

The story in the Pilbara region of diverse Precambrian igneous rock activity involving Archaean greenstone development and cratonisation, later Proterozoic volcanic and sedimentary rock sequences, and mafic dyke swarms meet the UNESCO Geopark criteria of having geological heritage of international significance.

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